SPACE SCIENCE IN THE UNITED STATES

The US space program continues to gather data from scientific spacecraft and from airborne experiments, despite the 1986 shuttle catastrophe. NASA has laid out an ambitious research program for the next five to ten years.

Joseph K. Alexander and Frank B. McDonald

Space research began as an exploratory endeavor, representing a natural evolution of science in which new opportunities were exploited and new capabilities were developed. The exploratory disciplines that originated with these early efforts, such as space physics, Earth remote sensing, planetary science and astronomy, have evolved and matured. They remain, in one way or another, fields that one might collectively describe as the science of space. On the other hand, several new disciplines that pertain to the pursuit of science in space are still in the early, developmental phase. These "microgravity sciences" involve investigations into basic physical, chemical and biological processes in very low gravity. Although research in these fields once possessed a certain Edisonian character—"let's try it and see what happens"—one now can see strong signs of sharpening scientific focus, maturing experimental capability and the promise of important scientific impact.

As scientists we are tempted to view the rationale for space research solely in terms of scientific criteria. The grand questions with which contemporary space researchers concern themselves are valid and compelling reasons for a space science program so long as that program can provide the resources and capabilities to permit them to be meaningfully pursued. However, one must also acknowledge other motivations for space research. The science of space, even when it provides practical information and applications, remains an enterprise of exploration. The perspective of space affords one a perception of humankind's place in the universe that cannot be gained in any other way. Moreover, the opportunity to send manned or robotic expeditions where no one has gone before captures a special spark in the human spirit. Space research, therefore, adds to the cultural richness that only an inquiring society can possess.

Space science can also be a powerful force in stimulating education and enhancing the quality of a nation's work force and technology base. As in other areas of basic science, difficult problems push creative people to find innovative solutions. Those solutions and the efforts to reach them have a way of making themselves felt outside the area of their origin. The challenge of space exploration can attract good students to science and engineering and can help motivate a technically literate population beyond the specific needs of the space program itself.

Elements of contemporary space research

Earth remote sensing and solar–terrestrial physics began with the first views of Earth from space, the first

Magellan Venus Orbiter will be the first science mission to be launched by the space shuttle after flights are resumed. The high-gain antenna (dish) sits atop the forward equipment module; the aperture in the module is the star tracker, and an altimetry antenna is mounted on the left side of the module and the dish antenna. Technicians adjust the struts surrounding the solid rocket motor and the solar panels (lower left and right). Projecting outward above their heads are two pairs of rocket engines for attitude maneuvering. (NASA photo)

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measurements of the topside of the ionosphere, and the discovery of the Earth's trapped radiation belts. Now researchers in these fields are on the verge of unraveling basic questions regarding the origins of solar variability and the mechanisms by which nonradiative energy from the Sun (that is, energy carried away by magnetized plasma and energetic particles) is coupled into the near-Earth environment. Space plasmas afford unique laboratory sites for studies of a variety of basic plasma instabilities, particle acceleration mechanisms and other particle–field interactions. In addition, the perspective of space is enabling Earth scientists to initiate the first quantitative multidisciplinary investigations of the Earth, including its atmosphere, oceans, land surface and biota, as an interactive system. These ambitious studies of long-term global change could have profound societal as well as intellectual impact.

In astronomy and astrophysics, the new windows in the electromagnetic spectrum surveyed by space-based observatories have stretched both the exploratory and the diagnostic abilities of astronomers dramatically. New classes of objects have appeared each time new wavelength regimes have been probed. Infrared observations from space have provided new insight into the early stages of star formation; x-ray measurements have provided new data on pulsars and supernovae; and measurements of cosmic gamma rays have shed new light (pun intended) on active galactic nuclei and have hinted at more exotic objects yet to be identified. Even in visible light, space observatories can provide unprecedented angular resolution and sensitivity.

Several trends in contemporary space astronomy are noteworthy. First, new subdisciplines are evolving. High-energy astrophysics, for example, has grown rapidly from x-ray and gamma-ray astronomy. Second, space-based experiments are being used to investigate some traditional fields of study, such as gravitational physics and relativity. The Stanford University experiment called Gravity Probe-B, which is being developed to provide critical tests of elements of the theory of general relativity, is a particularly noteworthy example. Third, and possibly most important, there is a growing synergism between previously independent specialties or subdisciplines. One no longer tends to classify astronomers by wavelength. Instead, astrophysicists are beginning to use all relevant tools and wavelengths to attack a given question. This approach, of course, represents the integration of space techniques into the mainstream of astrophysics, and a new level of maturity in the field.

Planetary science has blossomed in the space age, evolving from a minor subspecialty in astronomy into a "hands on" discipline. Space scientists have used robotic surrogates to perform initial reconnaissance of all Solar System planets except Neptune and Pluto; of the moons of Mars, Jupiter, Saturn and Uranus; and of two comets. They have placed instrumented landers on the surfaces of the Moon, Venus and Mars. Furthermore, the study of Earth's moon has progessed well beyond the exploration stage, with 12 men having walked its surface and carried back hundreds of kilograms of samples to Earth for analysis. Contemporary planetary scientists seek to understand the origin and evolution of the Solar System, the present state of the Earth (through comparative studies of other planets), and the chemical and biological evolution of life. As the level of sophistication of our research progresses from exploration to detailed study throughout the Solar System, these goals have come increasingly within reach.

A clear sense of direction and impact is just beginning to emerge in the youngest disciplines in the space sciences, the microgravity sciences. In addition to addressing the need for research to understand and ultimately prevent or ameliorate debilitating physiological effects of long spaceflights on humans, space biomedical research also may lead to a better understanding of physiological processes on Earth. Examples include bone demineralization (osteoporosis), cardiovascular deconditioning and endocrine function. There exists a broad range of topics in fundamental biology that one can hope to investigate in a microgravity environment. A particularly attractive application in biotechnology is the production of protein crystals, whose molecular structures can then be determined, using x-ray diffraction, for molecular engineering or pharmaceutical purposes. Such crystals, which often contain more than 50% water, can only be grown on the ground through tedious trial and error. In space, where the effects of sedimentation are removed, early experiments with protein crystal growth have been encouraging.

In the physical sciences, the microgravity disciplines also span a wide range of topics. Among the investigations being prepared are studies of critical phenomena that occur near liquid–vapor phase transitions such as the lambda point of superfluid helium. These experiments are being developed to test basic assumptions of the current scaling theory of critical phenomena. In the materials sciences, microgravity investigations can provide new insights into topics such as dendritic growth in metals and alloys, isothermal solidification of alloy melts and the relationship between the growth of materials used in electronics (for example, gallium arsenide crystals) and the role of defects in device performance. The microgravity environment also provides opportunities for fundamental studies in fluid dynamics and fluid mechanics. However, in none of the microgravity science specialties noted above have researchers demonstrated the feasibility or value of large-scale materials processing or manufacturing. Unique, one-of-a-kind samples of special materials may well be produced in the foreseeable future, but the principal goal of this work will continue to be understanding basic physical phenomena, rather than developing products, for some time to come.

US space science program today

Despite the long launch hiatus following the 1986 space shuttle catastrophe, the US space program is still producing new research data in most science disciplines. This resilience is a consequence of the fact that 18 scientific spacecraft are still operating productively in space and that researchers continue to use high-altitude aircraft, stratospheric balloons and sounding rockets to carry instruments aloft for limited investigations. (See the box on page 59.) For example, the Pioneer Venus Orbiter, launched in 1978, still operates in orbit about Venus, and Voyager 2, launched in 1977, will perform a close flyby of Neptune in 1989. Many instruments in Earth orbit continue to collect data on the Earth and on solar influences on the Earth's environment. Suborbital carriers such as aircraft, balloons and research rockets have played key roles recently in carrying instruments to study the depletion of stratospheric ozone above Antarctica and in making multispectral measurements of supernova 1987a. Research aircraft flying parabolic trajectories are also providing repeated short exposures to low gravity (on the order of 0.01 g for 20 seconds) in support of experiment development in the microgravity sciences. The extensive use of suborbital carriers, particularly as a means to train graduate students, is a characteristic of the US space program that distinguishes it from the programs of most other nations.

As the box on pages 60 and 61 indicates, NASA has

Currently Operating Spacecraft

Astronomy and astrophysics

▷ The International Ultraviolet Explorer, a cooperative mission with the European Space Agency, was launched in January 1978 to obtain high-resolution ultraviolet spectra of stars, planets and galaxies.

Solar System exploration

▷ Pioneer 10, launched in March 1972, was the first spacecraft to fly a reconnaissance of Jupiter and the first to leave our Solar System. Both it and Pioneer 11 continue to search for the heliospheric boundary and to investigate the outer Solar System.

▷ Pioneer 11 was launched in April 1973 as a second reconnaissance mission (including imaging) to Jupiter and Saturn.

▷ The Pioneer Venus Orbiter, launched in May 1978, has produced a radar altimetry map of the surface of Venus and continues to investigate the planet's atmosphere, ionosphere and solar wind interactions.

▷ Voyager 1, launched in September 1977, traveled to Jupiter (1979) and Saturn (1980) to study their atmospheres, satellites and rings. It continues to search for the heliospheric boundary and to conduct investigations of interplanetary space.

▷ Voyager 2, launched in August 1977, encountered Jupiter (1979) and Saturn (1981) with the same objectives as Voyager 1. It subsequently encountered Uranus in 1986, and it will fly past Neptune in 1989.

Space physics

▷ Pioneer 6, launched in December 1965, and Pioneer 8, launched in December 1967, are both in heliocentric orbit and continue to study interplanetary fields and particles, especially the solar wind and its relationship with Earth.

▷ Interplanetary Monitoring Probe 8, launched in October 1973, measures fields and identifies particles in the Earth's magnetosphere and the nearby solar wind.

▷ The International Cometary Explorer, launched in October 1978, was the first satellite to monitor the solar wind from the L_1 libration point halo orbit. It then explored Earth's magnetotail from a night-side orbit, with gravity-assist encounters with the Moon, and encountered the tail of comet Giacobini–Zinner in September 1985. A cooperative mission with the European Space Agency, it is now in interplanetary cruise.

▷ The Solar Maximum Mission, launched in February 1980, is conducting studies of solar flares and flare-related phenomena. It was the first spacecraft to be repaired in orbit.

▷ The Dynamics Explorer, launched in August 1984, creates images of the polar aurora and investigates plasma interactions between the magnetosphere and the ionosphere.

▷ The Charge Composition Explorer, launched in August 1984, has successfully completed the primary phase of the Active Magnetospheric Particle Tracer Experiment by tracking active chemical releases. A cooperative mission with West Germany and the United Kingdom, it is presently monitoring the equatorial magnetosphere.

Earth science

▷ Nimbus 7, launched in October 1978, collected the first global color data and continues to collect global ozone data.

▷ Landsat 4, launched in July 1982, and Landsat 5, launched in March 1984, are Earth remote sensing missions that provide multispectral images of land surfaces. Both are now operated by the Eosat Corporation.

▷ The Solar Mesosphere Explorer, launched in October 1981, continues to measure mesospheric ozone, the solar constant and solar effects on Earth's atmosphere.

▷ The Earth Radiation Budget Experiment, launched in August 1984, continues to make global measurements of solar radiation reflected and absorbed by the Earth.

laid out an ambitious program for the next five to ten years. The Hubble Space Telescope (to be launched from the space shuttle), the Cosmic Background Explorer (to be launched with a Delta rocket) and the Astro-1 Spacelab mission (shown on page 62) are scheduled for launch in 1989. Rosat, an x-ray astronomy mission developed by the Federal Republic of Germany, will carry a major US detector system and is scheduled to be launched in 1990 on a Delta rocket, and the Gamma Ray Observatory is to be launched from the space shuttle. In 1991 NASA plans a second flight of the Astro Spacelab mission and the launch of the Extreme Ultraviolet Explorer mission on a new reusable platform for moderately sized research payloads in low Earth orbit. NASA also hopes to begin development of two other major space observatories, the Advanced X-Ray Astrophysics Facility (targeted for a mid-1990s launch) and the Space Infrared Telescope Facility (targeted for launch in the late 1990s). These two facilities, in concert with the Hubble Space Telescope and the Gamma Ray Observatory, will culminate the establishment of four great observatories to cover the electromagnetic spectrum from infrared to gamma rays, and will provide astronomers with unprecedented viewing capabilities for over a decade.

In Solar System exploration, 1989 will mark the beginning of a series of launches of major missions, starting with the Magellan Venus radar mapper (shown on page 56), which should arrive at Venus in 1991, and the Galileo Jupiter atmospheric entry probe and orbiter spacecraft. To gain sufficient energy to reach Jupiter, the Galileo spacecraft will use gravitational kicks from close encounters with Venus in 1990 and with Earth in 1990 and 1992. Consequently it will also gather data during two passes through the asteroid belt before beginning its prime mission to Jupiter in late 1995. Galileo's trajectory is shown on page 63, and a schematic of the spacecraft appears on page 64. Ulysses, a cooperative mission with the European Space Agency, will be launched in 1990 on a trajectory that will take it on a close polar flyby of Jupiter in 1992, followed by a polar pass of the Sun in 1994 approximately 1 astronomical unit out of the ecliptic plane. Ulysses is noteworthy for its multidisciplinary character—it will address the physics of the Sun, the interplanetary medium and solar–planetary interactions. The Mars Observer spacecraft, scheduled for launch in 1992, will conduct detailed studies of climatological and geochemical characteristics of Mars. NASA hopes to initiate a program of advanced outer Solar System missions in the mid-1990s, by first conducting an extended close rendezvous with a comet and then by sending a mission with an atmospheric entry probe to Saturn's large moon Titan. Robotic exploration of the Martian surface and retrieval of samples for analysis on Earth remains a topic for study and a possible program goal for the end of the 1990s.

The International Solar–Terrestrial Physics program, a full suite of spacecraft scheduled for launch throughout the 1990s, will present an opportunity for a comprehensive international effort to study the solar–terrestrial energy chain from the interior of the Sun to the top of the Earth's atmosphere. Studies of the solar interior are now possible using the relatively new technique of helioseismology, in which one analyzes subtle oscillations on the Sun's surface to infer the characteristics of acoustic and gravitational waves in the interior. NASA plans to include a helioseismic experiment, as well as other instruments, on the European Space Agency's Solar and Heliospheric Observatory, which will be launched using a NASA expendable launch vehicle around 1995. In addition NASA will provide a portion of the instrument complement for ESA's four-spacecraft Cluster mission, scheduled for launch in 1995, to study the microphysics of space plasmas in the terrestrial magnetosphere and the nearby interplanetary medium. During the same time interval NASA will operate two US spacecraft, Wind and Polar, that will simultaneously measure energy transport to the Earth's vicinity by the solar wind and the subsequent deposition of energy in the polar auroral regions. Rounding out the network of measurements of plasma energy storage and transport in the magnetosphere will be the Combined Release and Radiation Effects Satellite, a joint US Air Force–NASA project scheduled for launch in 1990, and Geotail, a spacecraft provided by the Japanese Institute of Space and Astronautical Science that will be instrumented jointly by Japan and the US and will be launched by NASA in 1992.

Several major spaceflight studies of the Earth will begin in 1990, including the Atlas-1 Spacelab mission, which will carry a complement of solar and atmospheric monitoring instruments to study the total energy and spectral variability of solar radiation and to measure the global distribution of key molecular species in the middle atmosphere. The Upper Atmospheric Research Satellite will be launched from the shuttle in 1991 to study the chemistry and dynamics of the stratosphere and mesosphere. Also in 1991 France and the US will launch the joint TOPEX–Poseidon mission, via a French Ariane rocket, to record the topography of the oceans, thus measuring large-scale ocean circulation. Experiments on later shuttle flights will use synthetic aperture radar, imaging infrared spectrometers and lidar to study the Earth's surface, oceans and atmosphere.

The centerpiece of NASA's program to study the Earth as a whole will be the Earth Observing System. This system will comprise a full range of observing instruments, including meteorological sensors from the National Oceanic and Atmospheric Administration and an information system to manage the long-term database required to understand global change. The European Space Agency and Japan will collaborate on the endeavor and will provide polar orbiting platforms to carry complementary instrument payloads. NASA solicited research proposals earlier this year for participation in the program and hopes to be able to launch the first US platform in 1995.

NASA plans to use a series of Spacelab flights on the space shuttle to study the biological effects of microgravity. The first Spacelab Life Sciences mission will conduct a variety of investigations into acute physiological responses and short-term adaptation to microgravity in humans and animals, as well as several other problems in gravitational biology. A second Spacelab series, the International Microgravity Laboratories, will focus on crystal growth, fluid dynamics, plant gravitropism and human vestibular adaptation to weightlessness. US scientists will also conduct experiments on Japanese and

NASA's Planned Missions Through the 1990s

Astronomy and astrophysics

▷ The Cosmic Background Explorer, a small spacecraft to be launched in 1989, will study the spectrum and anisotropy of cosmic radiation (including the primordial background) in the wavelength range 1 μm to 10 mm.

▷ The Hubble Space Telescope, a 2.4-meter optical telescope with five focal plane instruments, will conduct spectroscopic, photometric and imaging studies at much higher sensitivity and resolution than possible from the ground. It will be launched in 1989.

▷ The Astro-Astrophysics Spacelab Payload has three complementary ultraviolet telescopes for spectroscopy, photopolarimetry and imaging applications. Space shuttle flights are planned in 1989 and 1991.

▷ The Gamma Ray Observatory will use four instruments to observe spectral and time variations of cosmic gamma-ray sources in the range 0.05 MeV to 30 GeV. It will be launched in 1990.

▷ The Extreme Ultraviolet Explorer, a small spacecraft to be launched in 1991, will use four grazing incidence telescopes to map the sky at extreme ultraviolet wavelengths.

▷ The Advanced X-Ray Astrophysics Facility, an x-ray telescope, will incorporate as many as four focal plane instruments for obtaining high-resolution, high-sensitivity spectroscopy and images of astronomical sources at wavelengths of 0.1–10 keV. Its launch is proposed for 1995.

Solar System exploration

▷ Magellan, a Venus orbiter to be launched in 1989, will use synthetic aperture radar to obtain global surface imagery and to study topography and geologic characteristics.

▷ Galileo, a Jupiter orbiter with an atmospheric entry probe, will be launched in 1989. It will study the Jovian atmosphere, magnetosphere and moons and will image several asteroids during its interplanetary cruise.

▷ The Mars Observer, a Mars orbiter to be launched in 1992, will conduct climatological and geochemical studies of the atmosphere and surface of Mars.

▷ The Comet Rendezvous–Asteroid Flyby is a proposed mission to make a close flyby of an asteroid and to maintain a multiyear close rendezvous with a comet. It would also send a penetrator probe into the comet's nucleus. Its launch is proposed for the mid-1990s.

▷ Cassini, a proposed Saturn orbiter, would send an entry probe into the atmosphere of Saturn's large moon Titan. Its launch is proposed for the late 1990s.

Space physics

▷ The Combined Release and Radiation Effects Satellite, a joint NASA–US Air Force project, will conduct active chemical release experiments and will study the Earth's trapped radiation belts. It will be launched in 1990.

▷ Ulysses, a joint NASA–European Space Agency mission, will study the heliosphere out of the ecliptic plane at distances of 1 astronomical unit above the solar poles. It will be launched in 1990.

▷ The Tethered Satellite System, a joint US–Italian project, will study the electrodynamics of a tethered instrument package deployed up to 20 km from the space shuttle. Its flight is planned for 1991.

▷ Wind is a spacecraft to be placed in the solar wind upstream of the Earth's magnetospheric bow shock as part of the Global Geospace Science program. Its launch is planned for 1992.

▷ Polar, a polar orbiter, will study magnetospheric plasma interactions and the physics of the aurora as part of the Global Geospace Science program. Its launch is planned for 1992.

▷ Geotail, a Japanese spacecraft carrying US and Japanese instruments, will study plasma interactions in the distant geomagnetic tail as part of the Global Geospace Science program. Its launch is planned for 1992.

Earth science

▷ The Upper Atmospheric Research Satellite, an orbiting platform, will study the chemistry, dynamics and energetics of

West German Spacelab missions that are scheduled to fly in 1991. NASA hopes to initiate a third series of Spacelab missions, called the US Microgravity Laboratory, that will be dedicated to investigations and instrument development in the materials sciences. In addition to these programs, NASA plans to fly packages of fully automated microgravity experiments on the shuttle about twice each year beginning in 1989, and several small experiments will be carried in mid-deck lockers in the shuttle crew compartment on each flight. NASA is also continuing a cooperative program with the Soviet Union on their Cosmos recoverable biosatellites. Twenty-six US principal investigators participated in studies of calcium metabolism, tissue biochemistry and histology, and radiation dosimetry on the 14-day flight of Cosmos 1887 in 1987, and planning is under way for a 1989 flight that may involve an even more extensive set of cooperative experiments.

Recent trends in the US space program

When one views NASA's proposed menu in the context of the history of the US program, some important trends become apparent. The number of space science mission launches fell from roughly ten per year in the mid-1960s, to five per year in the mid-1970s, to only about two or three per year in the early 1980s. The program planned for 1989–92 would restore the launch rate to five or more missions each year. Accompanying the drop in flight mission frequency has been an increase in the interval between the solicitation of research proposals for participation in a flight program and the actual launch of that program—from an average delay of about five or six years in the mid-1970s to about six to eight years by 1980. Space scientists are now facing waiting periods that range from as little as six to more than a dozen years. Tending to exacerbate this trend toward a slower pace in the program has been an increase in the number and breadth of the disciplines that compete for the program's resources, including money, manpower and launch vehicles.

At least two factors continue to strain NASA's ability to reverse the trend toward long time delays and lower flight frequency. First, the growing sophistication and complexity of new space missions are pushing researchers to develop larger, more costly space facilities. Second, the research community would like to develop large, long-lasting facilities, such as the Hubble Space Telescope and the Earth Observing System, that could serve its needs for more than a decade. However, such facilities carry a significant long-term operations cost.

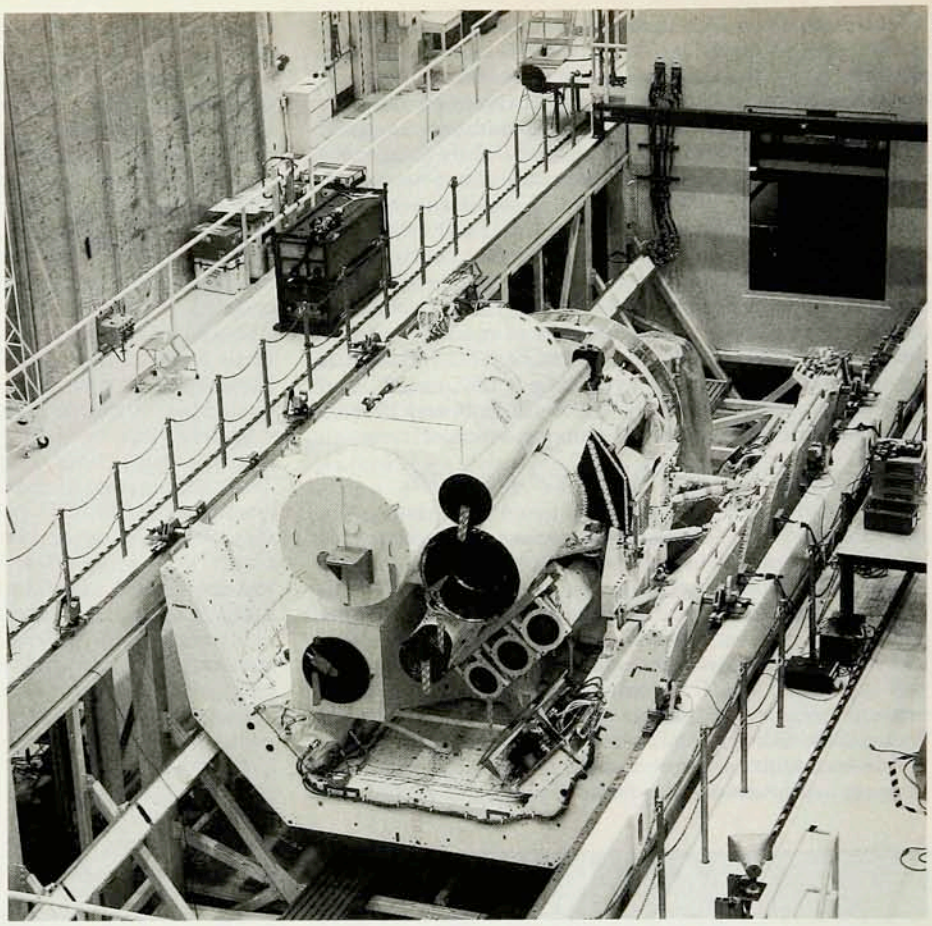
In their article on page 78, Louis Lanzerotti and Jeffrey Rosendhal discuss several steps NASA is taking to ensure that the US space science program remains vigorous. The agency has made a full commitment to return to a mixed fleet of launch vehicles. Additional resources have been obtained to augment the Explorer satellite program, which has traditionally been the means to fly small and moderate-class missions in physics and astronomy. With these new resources, a small-satellite element of the program is being introduced that will use rockets the size of the Scout vehicle, the smallest US vehicle capable of placing a payload in orbit. This new element of the program, for which proposals are being solicited this year, will restore a series of opportunities to conceive, develop and launch small experiments in a relatively short time and at a rate—just for this new program—of one or two per year. These efforts, then, will begin to restore a balance between small and large missions and will enhance the opportunities for graduate students to become substantively involved in all phases of a space research project.

A third trend, and in this case a positive one, has been developing for several years. Accompanying the escalating demand for space science resources have been an increasing appreciation within the research community of the need for clear priorities and an increasing willingness on the community's part to tackle the job of setting those priorities. Among the first such efforts was the work in 1982 of the Astronomy Survey Committee of the National Academy of Sciences, headed by George Field, which recommended priorities for all of astronomy in the US, including space astronomy.[1] This was followed by a recommended set of priorities and flight program strategies in planetary science, Earth science and life science developed for those disciplines by *ad hoc* committees operating under the aegis of the NASA Advisory Council, and a strategy for solar and space physics developed by a committee of the NAS Space Science Board.[2] Each of these discipline strategies is based on scientific goals and priorities established by the Space Science Board. Thus within each discipline, clear priorities defined by representatives of the research community itself are available to guide decision makers.

An important contribution to developing a rational process for making distinctions and choices among competing, but independent, disciplines (astrophysics versus biology, for instance) was made by the NASA Advisory Council's Space and Earth Science Advisory Committee.[3] That group, headed by Lanzerotti, defined a set of general criteria (including considerations of scientific merit, programmatic factors and societal implications) that can be applied to such deliberations. Using the SESAC criteria, the scientific priorities established by various advisory panels,

the stratosphere, mesophere and lower thermosphere. It will be launched in 1991.
▷ The Atmospheric Laboratory for Applications and Science, a Spacelab mission, would monitor variations in total solar irradiance and in the solar spectrum and would study the response of the atmosphere to those variations. Space shuttle flights are planned annually from 1990.
▷ The TOPEX–Poseidon experiment, a joint US–French project, will map the general circulation of the oceans from measurements of global ocean surface topography. An Ariane launch is planned for 1991.
▷ The Earth Observing System, a joint proposal by the US, the European Space Agency and Japan, would place research and operational sensors on polar orbiting platforms to study global interactions of the atmosphere, oceans, land and biota. Launches are proposed to begin in the mid- to late 1990s.

Microgravity sciences
▷ Spacelab Life Sciences, a series of Spacelab flights, will conduct studies of the physiological consequences of spaceflight and of gravitational biology. Three space shuttle flights are planned for 1990–93.
▷ The International Microgravity Laboratory, a series of Spacelab flights with international participation, will conduct experiments in life sciences, materials science and basic physics and chemistry. Space shuttle flights are planned for 1991, 1993 and 1994.
▷ Spacelab J, a joint US–Japanese Spacelab flight, will conduct multidisciplinary investigations in microgravity. A space shuttle flight is planned for 1991.
▷ Spacelab D, a joint US–West Germany Spacelab flight, will conduct multidisciplinary investigations in microgravity. Space shuttle flights are planned for 1991 and 1994.
▷ The United States Microgravity Laboratory, a proposed series of Spacelab flights, will focus on investigations in materials science and biotechnology. Space shuttle flights are proposed for 1992, 1993 and 1994.



Astro-1 Spacelab will carry several instruments, including (clockwise from upper left) the Hopkins Ultraviolet Telescope, the Advanced Star Tracker (narrow open-ended cylinder), the Ultraviolet Imaging Telescope (wide open-ended cylinder), the Spacelab Optical Sensor package (bank of three instruments), the Wide Field Camera (next to the optical sensor package) and the Wisconsin Ultraviolet Photopolarimetry experiment.

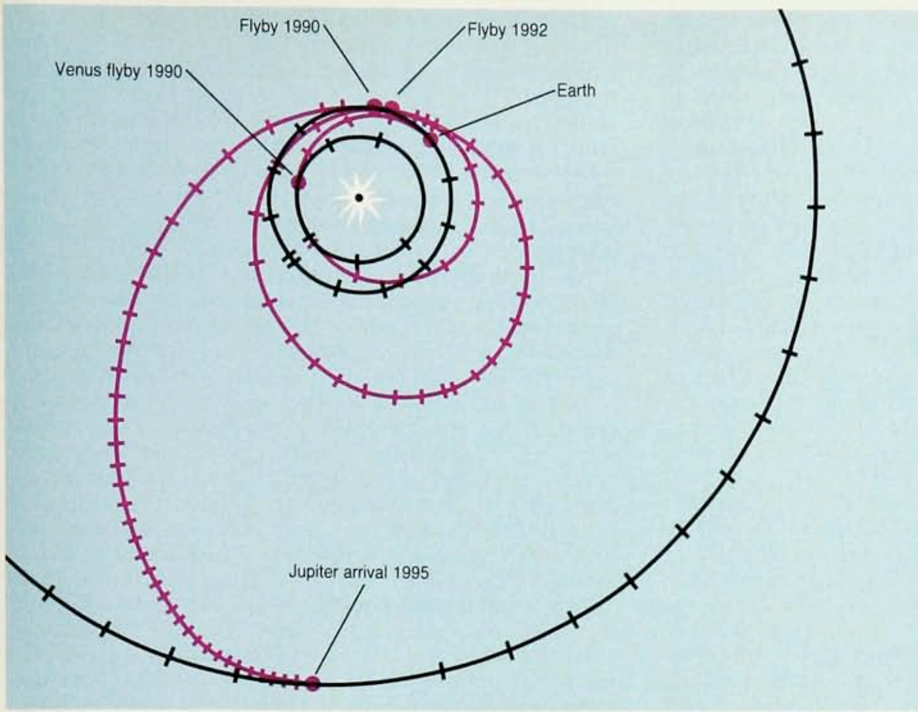
considerations of balance and vigor in the various disciplines, and attention to the need to maintain a mix of small and moderate-scale projects to complement the major missions, NASA has begun to develop a strategic plan that integrates the full spectrum of research disciplines.

International considerations

Although the early space program in the United States received a great impetus from concerns over competition with the Soviet Union, a sense of international cooperation has always been an important characteristic of space science. While that remains true today, certain aspects of space research sometimes do pose obstacles to international cooperation.

Science is an intrinsically international enterprise because fundamental scientific questions have no national boundaries. The opportunities provided by international participation for rapid advancement and for assuring the vigor born of a diversity of ideas are no less valuable in space science than in any other field. International cooperation has always been an attractive means of enabling researchers to exploit their resources to the utmost through cost sharing on joint projects, and that consideration has become even more important as space research projects have become more ambitious and more costly. In disciplines such as Earth science, international cooperation is essential to pursuing problems of a global nature, for example, in gathering "ground truth" data with which to calibrate remote sensing measurements. Finally, international scientific cooperation has been, and is likely to remain, an important vehicle for establishing international goodwill and for promoting a nation's foreign policy. Such cooperation permits technologically privileged nations to share the benefits of their technology with other nations, and it permits nations between which there may be strong political tensions to engage in nonthreatening, positive interactions.

As a counterpoise to the merits and motivations of international cooperation, we note three themes that can introduce resistance to such cooperation even in pure science. First, certain segments of the disciplinary spectrum of the space sciences are viewed as having important economic potential—for example, applications of microgravity technology to materials processing. The results of space research in these areas are expected by some to have an impact on international industrial competitiveness. In such cases, one finds arguments against open scientific cooperation because of the fear of losing the technological competitive edge. (Given the state of microgravity materials science, we suspect that there is still much more to be gained from cooperation than from restricting international scientific interaction.) A second obstacle to international cooperation is the drive to establish national preeminence and to demonstrate world leadership through prowess in space research. The high visibility of space research made the field an important symbolic activity at its very beginning, and it has remained so. Finally, open technological cooperation between geopolitical adversaries has always been viewed as a risk to national security. Consequently, concerns over unacceptable technology transfer to nations not allied with the United States have become significant elements in determining when and how international cooperation in space research can proceed. Today one sees some encouraging signs that the US and the USSR are using a step-by-step



Galileo mission to Jupiter begins with the planned launch of the spacecraft in October 1989. A gravity-assist flyby of Venus (February 1990) and two gravity-assist passes near the Earth (December 1990 and December 1992) provide the energy needed to reach Jupiter. Galileo's trajectory (colored line) and orbits for the Earth and Venus are marked at 30-day intervals; Jupiter's orbit is marked at 100-day intervals.

approach to developing cooperation in space science as a way to ease international tensions.

A US view of foreign space science

Throughout the 1980s a pluralistic, highly competent international space capability has emerged. Strong, independent space programs have been established in Europe and Japan, and the USSR has moved steadily toward an expanded, more open space research program, with a new emphasis on collaborative activities with Western Europe. Moreover, the Soviet Union has entered the space commercialization arena with its current marketing effort directed toward launch services (such as the expendable Proton vehicle), communications (as in the leasing of Gorizon transponders), and the leasing and flight of microgravity materials experiments (as on the Mir space station). China has placed 19 satellites into orbit, and its Long March 3 launcher features modern technology, such as liquid hydrogen–oxygen upper stages. Canada, India, Brazil and Australia also are increasing their space activities. The projected $2\frac{1}{2}$-year hiatus in US shuttle launches has dramatized the relative growth of international space programs after more than two decades of US dominance.

In his article on page 42, Ian Axford outlines major features of the West European space program. This program comprises both the 13-member European Space Agency and major national programs in France, Germany, Italy and Sweden. We estimate that the total *per capita* space research expenditures in Western Europe are significantly less than what the US civil program spends.

US cooperation with Western Europe has advanced from a policy of strong support by the US in the early 1960s to the exchange of experiments on US and European national spacecraft to a number of very successful cooperative programs. These latter have included the International Sun–Earth Explorer, the Infrared Astronomical Satellite, the International Ultraviolet Explorer, the Active Magnetospheric Particle Tracer Experiment and Helios.

In terms of quality, the West European space program is competitive with that of the United States. However, the participation of West European universities in space programs appears to be on a much smaller scale, relatively, than in the US. Western Europe has moved steadily toward greater independence in space by loosening its ties with the US and increasing its cooperation with the USSR, while strengthening its own space infrastructure. The West European space program has followed the trend toward larger, more complex and hence more expensive missions.

The beginning of the space age is defined by the launching of Sputnik I in October 1957. The orbiting of the first artificial Earth satellite and the flight of Yuri Gagarin on Vostok I in April 1961 were highly visible symbols of the accomplishment of Soviet technology and marked a major commitment to a strong national space effort. The Soviets appear to feel a rational, steady long-term space program will produce great political, scientific and technological gains, both by providing a technological push to the rest of their system and, on a global scale, by offering evidence that they are competitive with the US not only vis-à-vis national capability but also by virtue of their advanced technology. Historically the USSR and the US have continuously vied for dominance in this arena. The US responded to early Soviet achievements with programs such as Apollo, the Mariner missions, the Viking landing on Mars, and the Pioneer and Voyager explorations of the outer planets.

Over the past decade there has been a dramatic revitalization of the Soviet space research program, highlighted by such technological achievements as the Venera series of missions to study Venus, the two Halley probes, the Salyut series of space stations and the scheduled mission to study Mars and its satellite Phobos. The Soviets seem to be following a new policy of openness, whose manifestations range from televising manned launches live, to "opening" their space research centers to international visitors, to discussing their future research programs and actively seeking international collaboration. Roald Z. Sagdeev outlines the USSR space science program in his article on page 30.

We estimate that the total Soviet space science program expenditure is 1.8 percent of their GNP, while the US expenditure is 0.6 percent. Approximately 10 percent of their 80–100 annual launches are devoted to their manned program, and 8–10 percent support Soviet space science missions. The Soviets' extensive launch infrastructure and their assembly line production of spacecraft have yielded a greater capacity than they can use within their existing research capability. However, they are using this extra spaceflight capacity to make extensive experiment opportunities available to the scientists of Western Europe. This cooperation will significantly enhance the scientific quality of missions, and also will provide the Soviets with the use of, but not necessarily access to, new technologies. Such cooperation could be a highly visible way of building new political ties to the West.

Alternatives for future collaborations

The four major space programs—those of the US, the European Space Agency, the USSR and Japan—are experiencing significant growth that will enhance their individual research capabilities. As the space science community advances into a future of more ambitious concepts, such as 30-m reflectors for infrared studies, multimirror space interferometers and long-baseline gravity wave detectors, to name a few from astrophysics, the need for coordinated international collaboration will become even more compelling. It is crucial that scientists examine the various forms that future international collaborations might take.

One possibility is to extend the concept of the European Space Agency or of CERN to a global scale and establish a strong international space agency that would plan and manage a multinational space program. However, given the imperatives that drive the American, Japanese and Soviet programs, this approach is likely to be neither feasible nor desirable. It is doubtful that a strong global agency with direct program responsibility could be established, even though the concept has worked well on a regional basis.

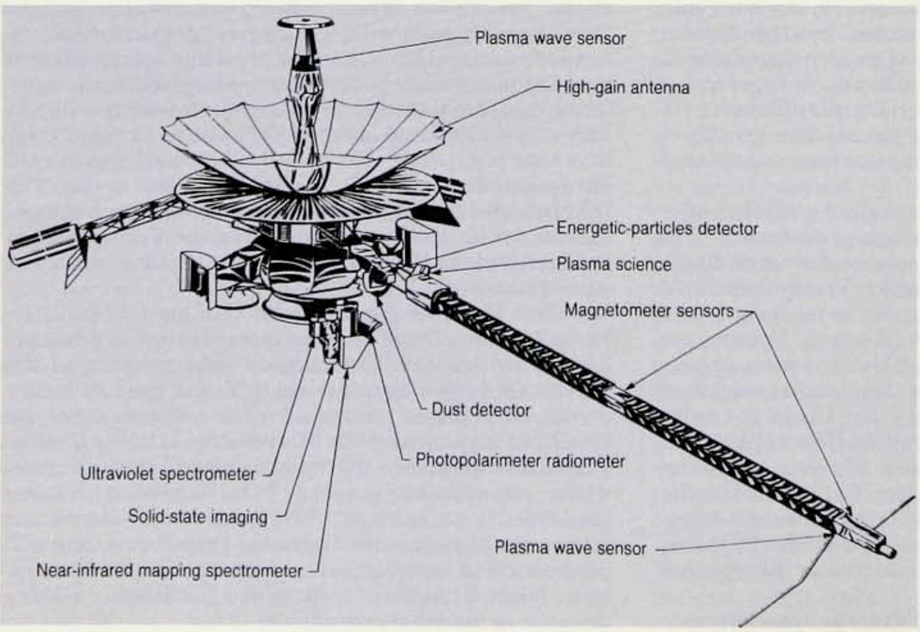
A very successful informal agreement on conducting the extensive activities associated with the Comet Halley encounter established an interagency group to coordinate mission operations and data from Earth observations and from five spacecraft sponsored by ESA, Japan and the USSR. For example, the US Deep Space network tracked the USSR's two Vega spacecraft to generate more precise Halley trajectory information for the ESA's Giotto spacecraft. A similar interagency group has been set up to coordinate the International Solar–Terrestrial Program. Such arrangements appear to be useful when individual agencies plan complementary missions in a given time interval.

A third approach to international cooperation might be arranging, by means of multilateral or bilateral agreements, a cartel among the various space agencies to coordinate a series of studies. This approach could minimize duplication and maximize scientific returns from the total available resources. For instance, one might divide the astrophysics program among various wavelength regions (radio, infrared, ultraviolet, x rays, gamma rays and cosmic rays) or plan complementary missions within a given spectral region (by using, for example, high-resolution spectroscopy or high-angular-resolution systems). A key feature of such research cartels should be that experiments for a given mission would be drawn from all interested space agencies and data would be shared on an equitable basis. The US has already participated in several agreements of this type: US spacecraft have carried European experiments and vice versa, and a joint French–US oceanography mission, TOPEX–Poseiden, is now well under way. These experiment exchanges have occurred with a minimum of technical difficulties. Such experiments essentially constitute "sealed black boxes" with defined mechanical, thermal and electrical interfaces, thus minimizing technology transfer.

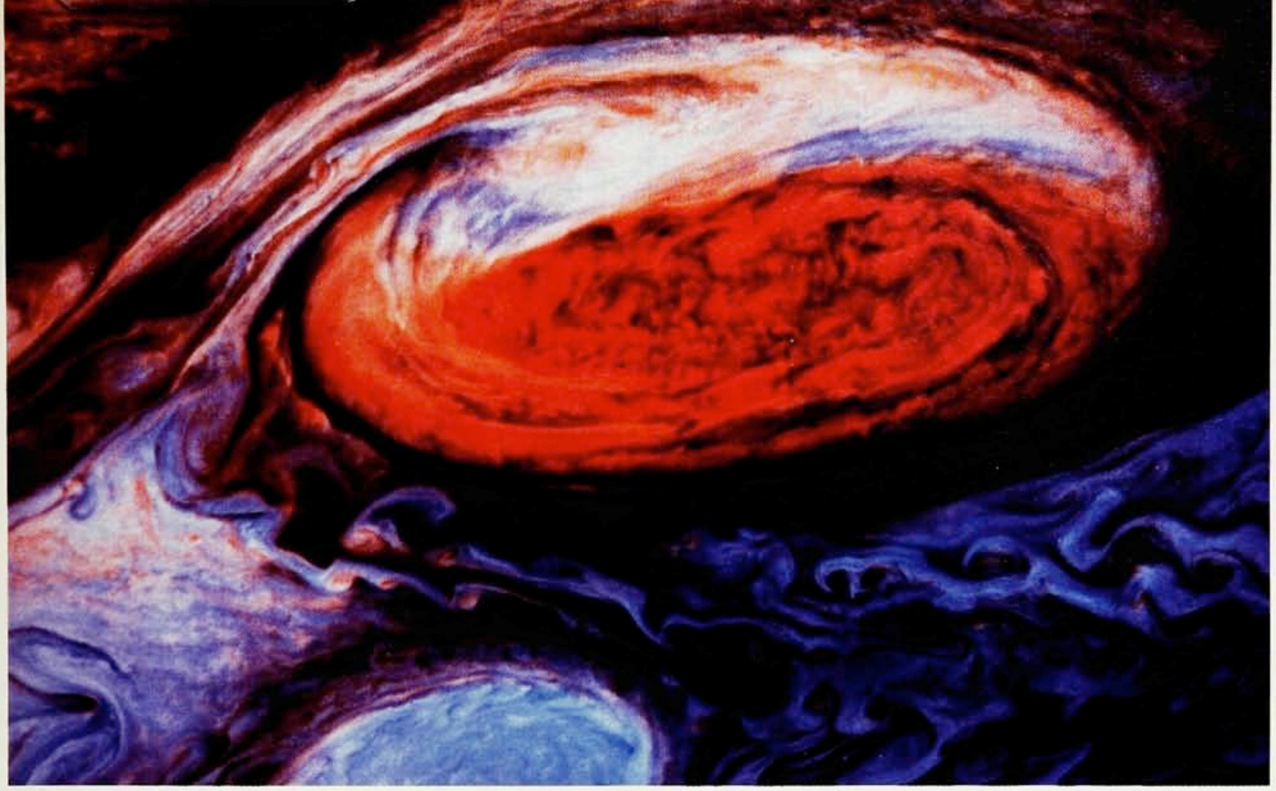
Long-range goals

There have been a number of important recent developments in space policy and in the setting of scientific goals for future programs. Of particular note are the report of the National Commission on Space entitled "Pioneering the Space Frontier"[4] and the Presidential directive on national space policy released on 11 February 1987.

In its report the National Commission on Space established three mutually supportive thrusts for the civil



Galileo orbiter, shown in this schematic, will make two traversals of the asteroid belt before arriving at Jupiter in 1995. It will deposit an instrumented probe into the Jovian atmosphere and then remain in orbit about Jupiter for continued scientific studies (adapted from a NASA diagram).



Voyager 2 made this false-color image of Jupiter's red spot in 1979. It subsequently encountered Saturn in 1981 and Uranus in 1986, and it should rendezvous with Neptune in 1989.

space program: advancing our understanding of our planet, the Solar System and the universe; exploring, prospecting and settling the Solar System; and stimulating space enterprises for the direct benefit of the people on Earth. The commission noted that implementing these thrusts requires an extensive program to develop new technologies and a greatly expanded infrastructure for space activities. The commission's well-balanced science goals generally reflect those being put forth in a long-range study by the National Research Council's Space Science Board entitled "Space Science in the 21st Century—Imperatives for the Two Decades 1995–2015."[5]

The Presidential directive defines the fundamental objective guiding US space activities as space leadership, requiring "preeminence in key areas of space activity critical to achieving our national security, scientific, technical, economic and foreign policy goals." The directive is strongly supportive of the civil space research program and establishes the concept of a mixed fleet of launch vehicles. It also proposes as a long-range goal the "expansion of human presence and activity beyond Earth orbit into the Solar System."

The possibility of human colonies on the Moon or Mars was a source of inspiration for early space pioneers and is perceived by some today as a means of promoting greater unity among the people on Earth. The proposal also receives strong support from many people closely associated with the US space program, who correctly perceive that the focused national effort behind the Apollo program triggered dramatic growth in our total science and applications program, as well as in our space research capabilities. However, the strength of the US space program today lies in its movement toward great diversity, which will drive the development of new technology. From a scientific standpoint, extensive exploration of Mars by balloons, penetrators, rovers and automated sample retrieval will yield greater returns at much lower cost, and will provide a strong stimulus to the development of automation, robotics, data systems and sensors.

Even if there is no concerted national effort in this direction over the next several decades, manned missions will undoubtedly set out to explore Mars, simply because heavy lift vehicles and a large space station for in-orbit assembly and research on the long-term physiological effects of a microgravity environment will be in place. Our best national strategy remains a vigorous, balanced program; exploiting the diversity of our space endeavors is the key to maintaining the quality of our research.

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